Case No.: Norte-513A

INTEGRATED NARROW-LINE TUNABLE OPTICAL PARAMETRIC OSCILLATOR

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] Not Applicable

STATEMENT RE: FEDERALLY SPONSORED RESEARCH/DEVELOPMENT

[0002] Not Applicable

BACKGROUND OF THE INVENTION

[0003] Optical Parametric Oscillation is a nonlinear process that converts a single input laser beam or a pump radiation source into two lower energy-beams known as the signal beam and the idler beam. The wavelengths/frequencies of the pump beam λ_{pump}/f_{pump}, $\lambda_{signal}/f_{signal}$, and $\lambda_{idler}/f_{idler}$ must satisfy:

$$\frac{1}{\lambda_{pump}} = \frac{1}{\lambda_{signal}} + \frac{1}{\lambda_{idler}} \qquad \text{(1), or equivalently}$$

$$\omega_{pump} = \omega_{signal} + \omega_{idler} \qquad (2)$$

Ideally, energy is conserved since the sum of photon energies of the signal beam and the idler beam is equal to the photon energy of the pump beam (The energy of a photon is proportional to the frequency thereof). There is no explicit requirement for the optical parametric oscillation to have the wavelengths of resulting beams related directly to the wavelength of the pump beam as long as the resulting beams satisfy the equations (1) and (2). Therefore, it is possible to implement a laser capable of being continuously tuned over a wide range of wavelengths by adjustment of the optical parametric oscillation only. In other words, the whole process can be tuned to create in effect a multicolor laser system - by changing the refractive index of the nonlinear crystal, which can be achieved by controlling temperature of the nonlinear crystal, or accomplished by rotating the crystal relative to the incident light beam.

[0004] Figure 1 shows a schematic setup of an optical parameter oscillator. As shown, a powerful radiation of a pump beam is generated from a pump laser 10 to propagate through an

optically nonlinear crystal 12 placed in an optical resonator comprised of a pair of mirrors 14. While traveling through the nonlinear crystal 12, a small portion of the pump beam is converted into a signal wave and an idler wave. The signal wave and/or the idler wave are fed back by the mirrors 14I and 14O of the optical resonator. For each propagation through the nonlinear optical crystal 12, the signal wave and/or the idler wave are amplified by a certain factor depending on the intensity of the pump beam. Each optical parametric oscillator has a characteristic pump intensity threshold. At and above the threshold, the amplification of the signal and idler waves compensates the resonator roundtrip loss caused by residual mirror transmission, crystal absorption, scattering, etc. Only if the optical parametric oscillator is pumped above the threshold, a significant amount of pump radiation is converted into signal and idler radiation. In practice, the input mirror 14I is designed with maximum reflectivity for the signal beam and/or idler beam, and the output mirror 14O determines whether the optical parametric oscillator is a singly or doubly resonant. That is, the output mirror 14O determines either one of or both the signal wave and the idler wave to be fed back to the nonlinear crystal and 12 resonated in the optical resonator.

[0005] Applications of optical parametric oscillation include light detection and ranging (LIDAR), high resolution spectroscopy, medical research, environmental monitoring, display technology and precision frequency metrology. In the coherent-detection applications of LADAR, vibrometry, and free-space optical (FSO) communication, a tunable, narrow-line, high-power source with wavelength (λ) of 1.5 microns is required. For example, coherent LADAR could require a source of about 10 Watts to about 100 Watts at a wavelength (λ) of about 1.54 microns with tunability of 1 nanometer over a 50 micro-second chirp, and linewidth as narrow as 50 KHz. It is likely that LADAR will rely on gas lasers to achieve these narrow linewidths in the near term. Similarly, airborne, free-space-optical communications will require a wavelength of about 1.5 micrometers with some tenability within the C-band and the linewidths of 100 KHz in a coherent-detection mode. Air-borne free-space-optical communication will rely on existing telecommunication components in the near term, such as a 1 micro-Watt laser diode, followed in series by erbium-doped fiber amplifiers (EDFA's) to achieve the power of 1-5 Watt. Polarizatio-maintaining erbium-doped fiber amplifiers are expensive; and moreover, high-end erbium-doped fiber amplifiers may provide no more than several Watts of power. As the airborne free-space-

optical range requirements increase, it is a challenge for sources to provide more power without sacrificing linewidth.

[0006] Research and development of applying nonlinear optics to the above missions have been commenced for years. For example, the pumping optical parameter oscillators (OPO's) with Nd:YAG laser sources are highly reliable to approach tunable, high-power sources. Materials used as the pumping optical parameter oscillators include periodically-poled lithium niobate ($LiNbO_3$ or PPN). With such material, a power of tens of Watts at a wavelength of about 1.064 micrometers can be pumped prior to approaching the laser-damage threshold thereof. However, these types of optical parametric oscillators tend to have fairly broad linewidth.

[0007] Narrow-linewidth operation (about 0.02 nanometer) of optical parametric oscillator has been achieved using a Littrow configuration disclosed in literatures such as "Littro Configuration Tunable External Cavity Diode Laser with Fixed Output Beam" by C.J. Hawthorn, K.P. Weber, R.E. Scholten in Review of Scientific Instrement, Vol. 72(12) pp4477-4479, Dec. 2001. Bosenberg et al. have also demonstrated a single-crystal optical parametric oscillator based on $KTiOPO_4$ (KTP), a grating and a tuning mirror. These disclosures indicated that fine tuning of one mirror provides a wavelength-selection mechanism, in which the optical parametric oscillator can be selectively seeded for a given narrow line. However, in these optical parametric oscillators, the resonator (the mirrors), the grating, and the nonlinear crystal are separate devices such that precise alignment is highly demanded, but it is laborious and time consuming. Further, the conventional tuning mirror still has the optical limit in tuning the light beam for achieving a fine and agile steering.

BRIEF SUMMARY OF THE INVENTION

[0008] The present invention provides an integrated optical parametric oscillator for converting a pump radiation into a signal wave and an idler wave, and to provide a fine tuning of the signal wave. The integrated optical parametric oscillator comprises an incident plane, an optical parametric oscillation region, a grating plane, an emerging plane, a reflecting plane and a fine-steering region. The incident plane is anti-reflective to the pump radiation and reflective to the signal wave and the idler wave, such that the pump radiation can transmit through the incident plane. After transmitting through the incident plane, the pump radiation is converted into the signal wave and the idler wave by the optical parametric oscillation region in front of the

incident plane. The signal wave and the idler wave are then incident on the grating plane. A portion of the signal and idler waves diffracted by the grating plane towards the emerging plane, and the other portion of the signal and idler waves is reflected towards the reflecting plane by the grating plane. The emerging plane is anti-reflective to the signal wave and reflective to the pump radiation and the idler wave. Therefore, the signal wave diffracted by the grating plane is allow to emerge via the emerging plane, while the idler wave diffracted by the grating plane is reflected by the emerging plane towards the grating plane or the incident plane. The reflecting plane is reflective to the pump radiation, the signal wave and the idler wave; and therefore, the other portion of the signal and idler waves reflected from the grating plane is reflected back to the grating plane. The fine-steering region is formed between the reflecting plane and the grating plane. The fine-steering region is operative to change the optical path of the signal wave incident onto the grating plane. As the signal wave is incident on the grating plane with a different incident angle, the signal wave is diffracted by the grating plane with a different wavelength. Thereby, the tenability is obtained.

[0009] Preferably, the incident plane, the optical parametric oscillation region, the grating plane, the emerging plane, the reflecting plane and the fine-steering region are integrated on a single slab of a nonlinear optical bulk material. The nonlinear optical bulk material includes lithium niobate crystal. The optical parametric oscillation region includes a part of the nonlinear optical bulk material being periodically poled, while the fine-steering region includes a part of the nonlinear optical bulk material and a pair of electrodes deposited on two opposing surfaces of thereof. That is, the fine-steering region includes a part of the nonlinear optical bulk material subjected to an electric field. In one embodiment, the pump radiation has a wavelength of about 1.064 micrometers, the signal wave has a wavelength of about 1.54 micrometers, and the idler wave has a wavelength of about 3.442 micrometers. Alternatively, the pump radiation has a wavelength of about 1.064 micrometers, the idler wave has a wavelength of about 1.54 micrometers, and the signal wave has a wavelength of about 3.442 micrometers. The grating plane includes a holographic grating with about 200 to about 500 grooves/mm, for example.

[0010] The present invention also provides an integrated optical parametric oscillator, comprising a nonlinear optical bulk material, which includes a locally periodically poled region and a steering region subjected to an electric field. The nonlinear optical bulk material includes a lithium niobate, and the locally periodically poled region has a length of about 30 mm. The

nonlinear optical bulk material further comprises a plurality of exterior coated planes forming a resonator of a wave at predetermined wavelength.

[0011] The present invention further provides a tunable, narrow-line laser system comprising a pump radiation source and an integrated parametric oscillator. The pump radiation source is operative to generate a pump radiation. The integrated optical parametric oscillator comprises a nonlinear optical bulk crystal. The nonlinear optical bulk crystal countered with an incident plane, a grating plane, an emerging plane and a reflecting plane. Between the incident plane and the grating plane, an optical parametric oscillation region is formed. Between the grating plane and the reflecting plane, a fine-steering region is formed. The incident plane is anti-reflective to the pump radiation, which that the pump radiation can enter the nonlinear optical bulk crystal by transmitting through the incident plane. The optical parametric oscillation region is operative to convert the pump radiation into a signal wave and an idler wave. A portion of the signal and idler waves is diffracted towards the emerging plane by the grating plane, while the other portion of the signal idler waves is reflected from the grating plane to the reflecting plane. The emerging plane allows the diffracted signal wave to transmit through, while reflects the diffracted idler wave back to the grating plane or the incident plane. Meanwhile, the signal and idler waves reflected from the grating plane being reflected from the reflecting plane back to the grating plane. However, as a fine-steering region is formed between the reflecting plane and the grating plane. An optical path difference of the reflected portion of the signal and idler waves is generated. Therefore, the incident angle of reflective portion of the signal wave is changed; thus provides wavelength tenability.

[0012] Preferably, the pump radiation source includes a Nd:YAG laser operative to generate a pump radiation with a wavelength of about 1.064 micrometers. The nonlinear optical bulk crystal includes a lithium niobate crystal. The optical parametric oscillation region includes a periodically poled region of the nonlinear optical bulk crystal with a length of about 30 mm. The optical oscillation region is operative to convert the pump radiation into the signal wave with a wavelength of about 1.54 μm and the idler wave with a wavelength of about 3.442 μm. Or alternatively, the optical oscillation region is operative to convert the pump radiation into the signal wave with a wavelength of about 3.442 μm and the idler wave with a wavelength of about 1.54 μm. The steering region includes a region of the nonlinear optical bulk crystal subjected to

an electric field. Preferably, the incident plane, the grating plane, emerging plane, and the reflecting plane are all reflective to the idler wave and arranged as a resonator of the idler wave.

BRIEF DESCRIPTION OF THE DRAWINGS

[0013] These, as well as other features of the present invention, will become apparent upon reference to the drawings wherein:

[0014] Figure 1 shows a conventional optical parametric oscillator;

[0015] Figure 2 shows a schematic drawing of an integrated optical parametric oscillator; and

[0016] Figure 3 shows the optical path of the pump wave, the signal wave and the idler wave within the integrated optical parametric oscillator.

DETAILED DESCRIPTION OF THE INVENTION

[0017] The present invention provides an optical parametric oscillator which integrates all critical components of the above Littrow configuration into a single slab of nonlinear optical material. As shown in Figure 2, the optical parametric oscillator includes a single slab of nonlinear optical bulk material 20, preferably a lithium-niobate crystal ($LiNbO_3$). By locally poling the nonlinear optical bulk material 20 periodically, a part of the nonlinear optical bulk material 20 is processed as an optical parametric oscillation region 22 operative to convert a pump radiation λ_p into waves with wavelengths longer than that of the pump radiation λ_p. As mentioned above, the converted waves include one signal wave λ_s and one idler wave λ_i. For example, when the wavelength of the pump radiation λ_p is about 1.064 microns, the wavelengths of the signal and idler wave λ_s and λ_i converted by the optical parametric oscillation region 22 are about 1.54 microns and 3.442 microns. Preferably, the optical parametric oscillation region 22 has a length of about 30 mm. In addition to the optical parametric oscillation region 22, the nonlinear optical bulk material 20 further includes a fast, ultra-fine-steering region 24, which is formed by depositing electrodes 26 on both sides of another part of the nonlinear optical bulk material 20. By applying an electric field across the steering region 24 via the electrodes 26, the refractive index of the steering region 24 is modulated, such that an optical path difference is

induced to an optical wave propagating through the steering region 24. The optical path difference of the optical wave is proportional to the modulation of refractive index as:

$$\mathrm{OPD}(x) = nL(x) \qquad (3),$$

where $\mathrm{OPD}(x)$ is the optical path difference along an x-axis, which is the propagating direction in this embodiment, n is the refractive index of the steering region 24, and $L(x)$ is the effective length of the steering region 24. The modulation of the refractive index n is a function of the electric field.

[0018] As shown in Figure 2, the nonlinear crystal bulk material 20 is countered to have several exterior planes, including an incident plane 201, a grating plane 202, a reflecting plane 203 and an emerging plane 204. The integrated optical parametric oscillator further comprises at least three coatings 31, 32 and 33, and a holographic grating 34 formed on incident plane 201, the reflecting plane 202, the emerging plane 203 and the grating plane 204, respectively. The coatings 31, 32 and 33 are designed to be anti-reflected for light waves with predetermined wavelengths and highly reflective for light waves with other predetermined wavelengths. In this embodiment, a Nd:YAG laser pump source is selected to generate the pump radiation λ_p with the wavelength of about 1.064 microns, and the optical parametric oscillation region 22 is operative to convert the pump radiation λ_p into a signal wave λ_s at 1.54 microns and an idler wave λ_i at about 3.442 microns. The coating 31 is highly reflective to the signal and idler waves λ_s and λ_i and anti-reflective to the pump radiation λ_p. The coating 32 is highly reflective to the pump radiation λ_p and the idler wave λ_i and is anti-reflective to the signal wave λ_s. The coating 33 is highly reflective to all of the pump source λ_p, the signal wave λ_s and the idler wave λ_i. When a light is incident onto the holographic grating 34, depending on the incident angle α, some of the incident light is diffracted and dispersed, and some of the incident light is reflected. Therefore, almost 100% of the pump radiation λ_p incident on the coating 31 will transmit through the coating 31, while most of the signal and idler waves λ_s and λ_i will be reflected thereby. The signal wave λ_s will transmit through the coating 32, while the pump radiation λ_p and the idler wave λ_i will be reflected thereby. Regarding the coating 33, all of the pump radiation λ_p, the signal wave λ_s and the idler wave λ_i will be reflected thereby. As all of the coatings 31, 32 and 33 are highly reflective to the idler wave λ_i, the idler wave λ_i will thus be resonated within the nonlinear optical bulk material 20. It will be appreciated that by adjusting the reflective characteristics of the coatings 31, 32 and 33, different wave, for example, the signal wave λ_s will

be resonated within the nonlinear optical bulk material 20, while the idler wave λ_i can be coupled out. Alternatively, one can also design a doubly resonant optical parametric oscillator by adjusting the reflective characteristics of the coatings 31, 32, 33 and the grating 34.

[0019] Figure 3 shows the optical paths of the pump radiation λ_p, the signal wave λ_s and the idler wave λ_i. As shown in Figures 2 and 3, the optical parametric oscillation region 22 is located immediately in front of the incident plane 201 along the optical path of the pump radiation, such that after transmitting through the coating 31, the pump radiation λ_p is converted into the signal wave λ_s at 1.54 microns and the idler wave λ_i at 3.442 microns. The reflective characteristics of the coating 31 ensure that the pump radiation λ_p is the only input of the integrated optical parametric oscillator. On the other hand, in the situation that the signal and idler waves λ_s and λ_i generated by the optical parametric oscillation region 22 are reflected back to the coating 31, the high reflectance of the coating 31 will then reflect these waves back to the nonlinear optical bulk material 20. Therefore, the loss due to reflection or other optical effect can be minimized.

[0020] The signal wave λ_s and the idler wave λ_i are then incident on the holographic grating 34. In other word, the optical parametric oscillation region 22 is located between the incident plane 201 and the grating plane 204 along optical path of the pump radiation λ_p as well as the signal and idler waves λ_s and λ_i. As known in the art, when a light is incident on the holographic grating 34, some of the light is reflected thereby, while some of the light diffracted thereby will be separated (dispersed) into its constituent monochromatic components. The component dispersed by the grating depends on the incident angle of the light as:

$$m\lambda = d(\sin\alpha + \sin\beta) \qquad (4),$$

where m is the diffraction order, d is the groove spacing of the grating 34, α is the incident angle to the grating 34, and β is the diffraction angle by the grating 34. Therefore, by adjusting the incident angle α, both the signal wave λ_s and idler λ_i can be tuned with desired wavelengths. The holographic grating 34 used in this embodiment has 200 to 500 grooves per millimeter, for example. In this embodiment, as the holographic grating 34 is permanently attached to or integrated on the grating plane 304, the adjustment upon the incident angle α of the incident light (both the signal and idler waves λ_s and λ_i) cannot be achieved by orienting the holographic grating 34. In addition to the pre-designed geometry of the nonlinear optical bulk material 20, a raw adjustment of the incident angle α is achieved by adjusting the incident angle of the pump

source λ_p onto the incident plane 201. In this embodiment, the raw adjustment is performed allowing a portion of the incident light (the signal and idler waves λ_s and λ_i) reflected by the holographic grating 34 towards the reflecting plane 202, and the other portion of the incident light diffracted by the holographic grating 34 towards the emerging plane 203.

[0021] In this embodiment, the coating 33 is designed to be anti-reflective at 1.54 microns and highly reflective at 3.442 microns; and therefore, the signal wave λ_s' diffracted by the holographic grating 34 transmits through the coating 33. It is appreciated that as the signal wave λ_s' has been diffracted and dispersed by the holographic grating 34, the wavelength of the output wave may deviate from 1.54 microns. Meanwhile, and idler λ_i' diffracted by the grating 34 is reflected by the coating 33 towards either the coating 31 or the grating 34 and reflected towards the coating 32. As all of the coatings 31, 32 and 33 and the holographic grating 34 are highly reflective at the wavelength of the idler wave λ_i (λ_i'), the idler wave λ_i is resonating within the nonlinear optical bulk material 20.

[0022] While the portion of the signal wave λ_s' diffracted by the holographic grating 34 emerges from the emerging plane 203 as the output wave, the other portion of the signal wave λ_s" reflected by the holographic grating 34 propagates through the steering region 24 towards the coating 32. The signal wave λ_s" is then reflected by the coating 32 and incident on the holographic grating 34 again. As mentioned above, by applying an electric field across the steering region 24, the optical path of the signal wave λ_s" is deviated. One can control the electric field to induce the optical path difference when the signal wave λ_s" is propagating from the holographic grating 34 to the coating 32, and/or when the signal wave λ_s" is propagating from the coating 32 to the holographic grating 34. Thereby, being reflected by the coating 32, the modulated signal wave λ_m is incident onto the holographic grating 34 with a different incident angle α'. In Figure 3, the dashed line showing the optical path of the signal wave λ_s" reflected from the reflecting plane 202 to the grating plane 204 without being modulated. As a result, the signal wave λ_m is diffracted with a desired wavelength. The diffracted signal wave λ_m is then emerging from the emerging plane 203 as the output of the integrated optical parametric oscillator. In this embodiment, the signal wave λ_s" propagating through the steering region is steered with an angle of about $\pm 1^{\circ}$. Such fine steering results in a fine adjustment of the wavelength tuning in nanometers.

[0023] This disclosure provides exemplary embodiments of an integrated optical parametric oscillator. The scope of this disclosure is not limited by these exemplary embodiments. Numerous variations, whether explicitly provided for by the specification or implied by the specification, such as variations in shape, structure, dimension, type of material or manufacturing process may be implemented by one of skill in the art in view of this disclosure.